

Comparison of Capture Point Estimation with Human Foot Placement: Applicability and Limitations

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Outline

- 1 Context
- 2 Capture Point/Region Estimation
- 3 Analysed Experimental Data
- 4 Results
- 5 Conclusion and Perspective

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Motivation

- Risks related to passengers' loss of equilibrium in Public Transport vehicles
 - Abrupt acceleration changes
 - Discomfort and Casualties
 - Standing passengers' vulnerability (65% of all injured passengers ¹)
 - A serious issue that may have social impacts



¹ Bjornstig et al., Injury events among bus and coach occupants-non-crash injuries as important as crash injuries, IATSS research, 2005

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A problem that needs to be addressed

¹ Bjornstig et al., Injury events among bus and coach occupants-non-crash injuries as important as crash injuries, IATSS research, 2005

Scope of the study

Fundamental Question:

How do people react when their equilibrium is disturbed ?

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Key Features:

- Standing posture
- Disturbance of moving platform type
- Duration of disturbance relatively long
- A diverse population

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Fundamental Question:

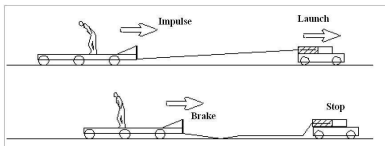
How do people react when their equilibrium is disturbed ?

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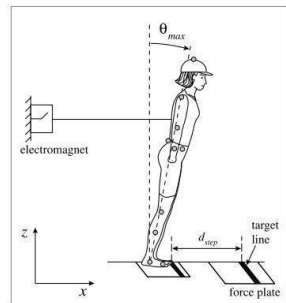
- Standing posture
- Disturbance of moving platform type
- Duration of disturbance relatively long
- A diverse population
- Multidirection Disturbance
- Different standing postures

Human Balance Recovery after disturbance

- A problem mostly attacked using experiments
- Exposing volunteers to representative situations (slips, pushes, transport etc.)
- Recording their reactions with the help of instrumentation (reflexive markers, force plates etc.)



Robert et al., Int J of Crashworthiness, 2007



Hsiao et al., Clinical Biomech, 2007

Limitations

Experimental results are difficult to generalize because of their dependence upon:

- The type of disturbance applied (moving platform, waist-pull etc.)
- The properties of the disturbance applied (duration, profile)
- The instructions given (stepping or not)
- The age-group under consideration

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Need an elaborate model which explains:

- How the reaction changes by varying the stimulus properties ?
- How the reaction changes by population ?

Final Objective

- To develop a dynamic simulation of Balance Recovery
 - Application to standing passengers of public transport
 - Simulation of reaction of different groups of population, especially the Elderly

Working in 2 Labs

■ Biomechanics, LBMC, INRETS

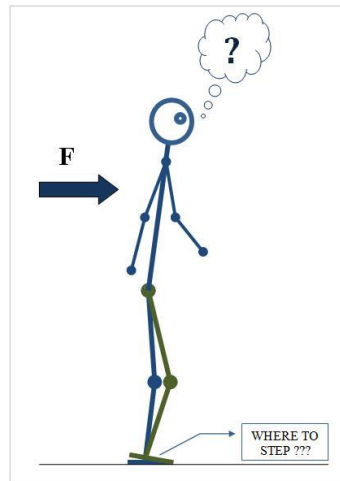
- Analysis of experimental data
- Synthesis of balance recovery parameters

■ Robotics, INRIA Rhone-Alpes

- Dynamic control techniques
- Identification of model parameters
- Exploitation of simulation tools

Today's Topic

- Prediction of Human foot placement under a large postural disturbance
- Comparison of laboratory acquired experimental data with an existant stepping prediction model



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Definition and Assumptions

An algorithm developed by Pratt et al.^{2 3} to estimate recovery foot location for biped robots

Capture Point

- A point on the ground where a biped must step and maintain its center of pressure to stop itself completely in a *single step*
- A unique point corresponding to instantaneous state of the biped

Assumptions

- Linear inverted pendulum model (LIPM)
- *Instantaneous* foot placement

² Capture Point: A step toward Humanoid Push Recovery, Humanoids 2006

³ Velocity-based stability margins for fast bipedal walking, Springer 2006

Consideration of Point Mass

Basic Dynamic Equation:

$$\ddot{x} = \frac{g}{z_0}(x - x_p) \quad (1)$$

Orbital Energy:

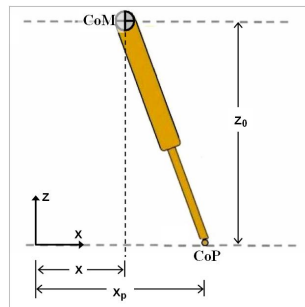
$$E_{LIP} = \frac{1}{2}\dot{x}^2 - \frac{g}{2z_0}(x - x_p)^2 \quad (2)$$

CoM will rest over the foot if $E_{LIP} = 0$

$$0 = \frac{1}{2}\dot{x}^2 - \frac{g}{2z_0}(x - x_p)^2$$

$$\Rightarrow \dot{x} = \pm(x - x_p)\sqrt{\frac{g}{z_0}} \quad (3)$$

We are interested in foot placement and the stable eigenvector:



$$x_p = x + \frac{1}{\omega}\dot{x} \quad (4)$$

where $\omega = \sqrt{\frac{g}{z_0}}$

Consideration of upper-body inertia

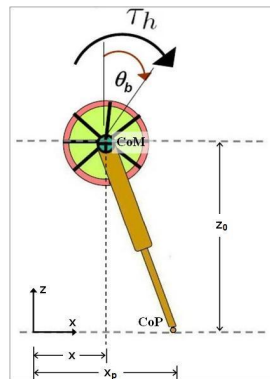
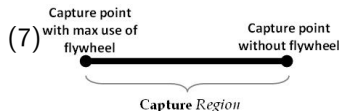
Flywheel Model:

$$\begin{aligned}\ddot{x} &= \frac{g}{z_0}(x - x_p) - \frac{1}{mz_0}\tau_h \\ &= \omega^2(x - x_p) - \frac{1}{mz_0}\tau_h\end{aligned}\quad (5)$$

Bang-Bang Profile:

$$\begin{aligned}\tau(t) &= \tau_{max}u(t) - 2\tau_{max}u(t - T_{R1}) \\ &\quad + \tau_{max}u(t - T_{R2})\end{aligned}\quad (6)$$

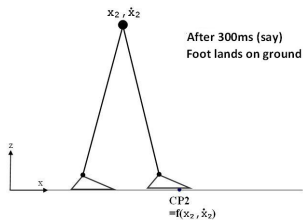
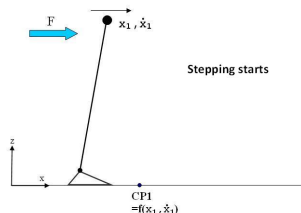
$$x_p = x + \frac{1}{\omega}\dot{x} - \frac{\tau_{max}}{mg}\left[\frac{e^{\omega T_{R2}} - 2e^{\omega(T_{R2}-T_{R1})} + 1}{e^{\omega T_{R2}}}\right]$$



Model during legswing phase

Estimation of capture point evolution

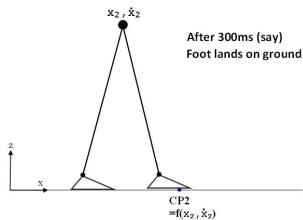
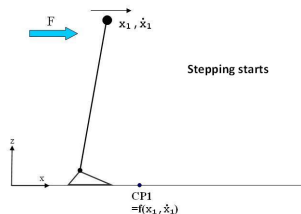
- Capture point algorithm assumes zero time-delay between step initiation and landing
- Correct estimation of capture point requires its evolution during legswing phase



Model during legswing phase

Estimation of capture point evolution

- Capture point algorithm assumes zero time-delay between step initiation and landing
- Correct estimation of capture point requires its evolution during legswing phase
- 2 models of CoM evolution considered



Estimation of capture point evolution

Estimation using LIPM

$$z = \text{constant}$$

$$x(t) = x_0 \cosh(\omega t) + \frac{1}{\omega} \dot{x}_0 \sinh(\omega t)$$

$$\dot{x}(t) = \omega x_0 \sinh(\omega t) + \dot{x}_0 \cosh(\omega t)$$

Estimation using Freefall model

$$\ddot{z} = g$$

$$\dot{x} = \text{constant}$$

$$x(t) = x_0 + (\dot{x} \times t)$$

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Use of basic equation

$$x_p = x + \frac{1}{\omega} \dot{x}$$

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Estimation using Freefall model

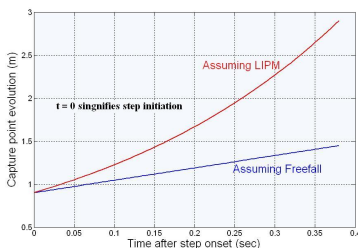
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Use of basic equation

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Purpose

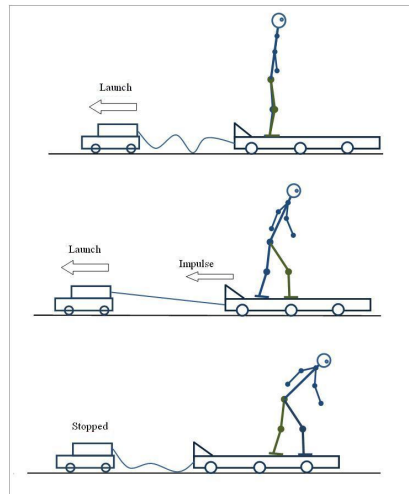
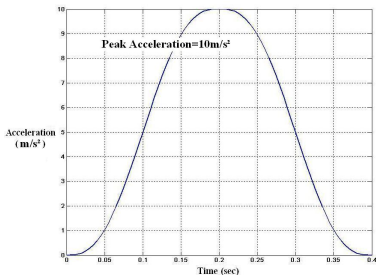
To compare the experimental results with these curves and find out which model is more realistic during stepping

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Disturbance Mechanism

- Young healthy volunteers⁴
- Disturbance induced by moving platform backwards
- Duration of impulse: 400ms

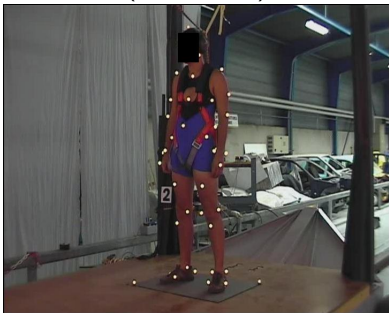


⁴ Robert T., Thèse de doctorat, INSA Lyon, 2006

Experimental procedure

2 series of experiments

Large space to take several steps
(8 subjects)



Limited space (800mm)
(4 subjects)



Calculations

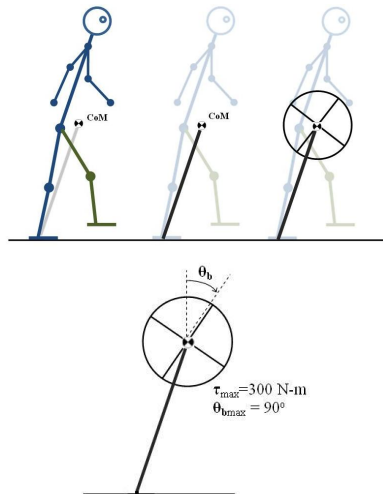
■ Stepping parameters:

- No of steps to recover (n)
- Times of 1st step initiation and landing
- Time duration of 1st step (t_{step})

■ From Motion reconstruction:

- Center of Mass state (position and velocity) for each subject ($CoM_{exp}(t)$)
- Capture Point Estimation ($CP_{exp}(t)$)
- Capture Region Estimation ($CR_{exp}(t)$) using typical maximum values⁵

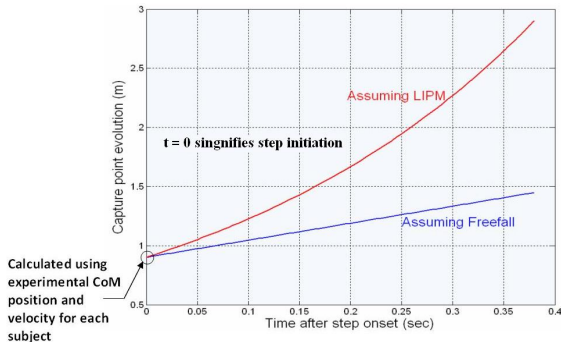
■ 2 key instants noted: Step initiation and foot landing on ground



⁵ Chaffin D., Andersson G., Martin B., Occupational Biomechanics, Wiley & Sons, 1999

Further Calculations

- Using (CoM_{exp}) at step initiation, estimation of Capture Point evolution during t_{step} using the 2 models

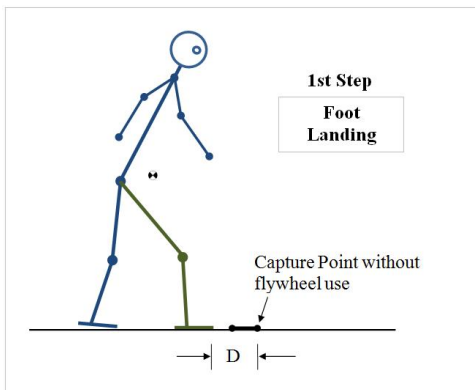


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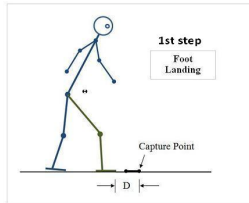
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Human foot placement w.r.t. CP_{exp} vs No of steps (n)

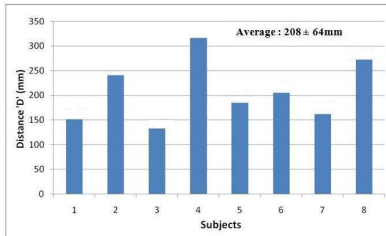
Is the capture point algorithm corresponds well with our experimental results ?



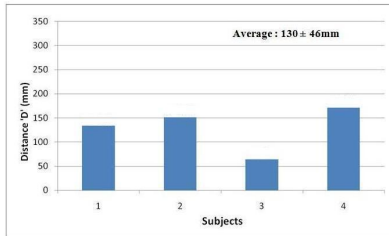
Experimental Results

Human foot placement w.r.t. CP_{exp} vs No of steps (n)

Case I: Large space provided



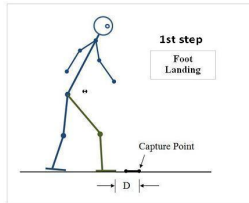
Case II: Limited space provided



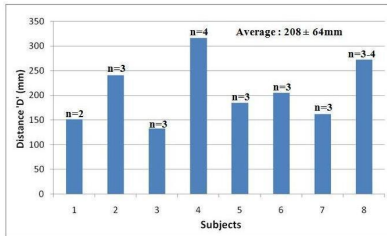
Experimental Results

Human foot placement w.r.t. CP_{exp} vs No of steps (n)

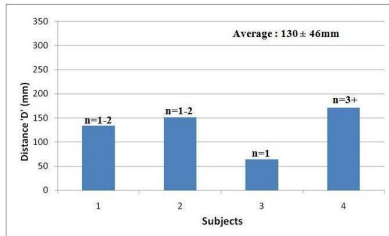
n = number of steps taken to recover completely



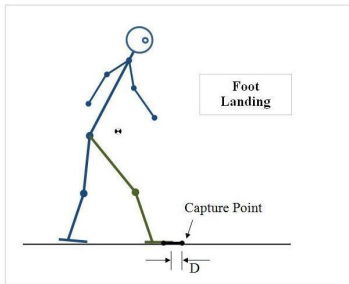
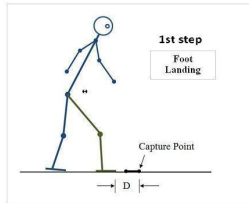
Case I: Large space provided



Case II: Limited space provided

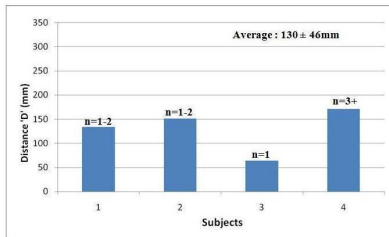


Experimental Results

Human foot placement w.r.t. CP_{exp} vs No of steps (n)

Case II, Subject 3

Case II: Limited space provided



Human foot placement w.r.t. CP_{exp} vs No of steps (n)

Observations

Distance of foot with respect to capture point at landing (D) gives an indication of the number of steps (n)

One subject steps on capture region and recovers perfectly in single-step

Result 1 \Rightarrow LIPM seems to be a reasonable model for single-step predictions

Behaviour during legswing phase

Which model better represents the legswing phase ?

Objective To predict capture point location at foot landing

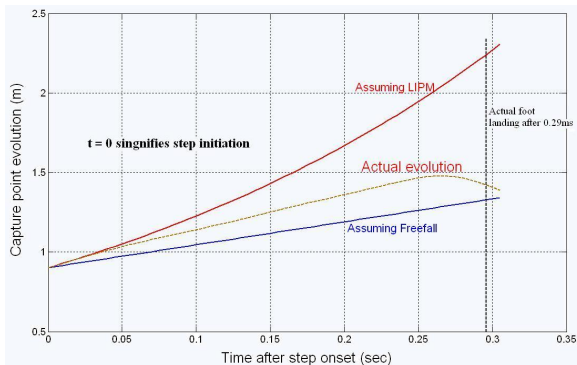
Comparison of experimental capture point evolution over time with the prediction models

Behaviour during legswing phase

Which model better represents the legswing phase ?

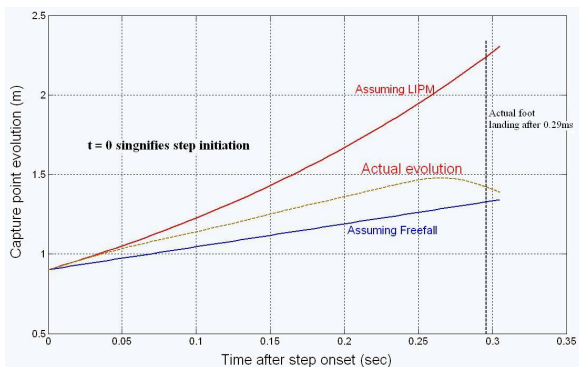
Objective To predict capture point location at foot landing

Comparison of experimental capture point evolution over time with the prediction models



Behaviour during legswing phase

Result 2 \Rightarrow The hypothesis of LIPM not obeyed during the legswing phase in our case



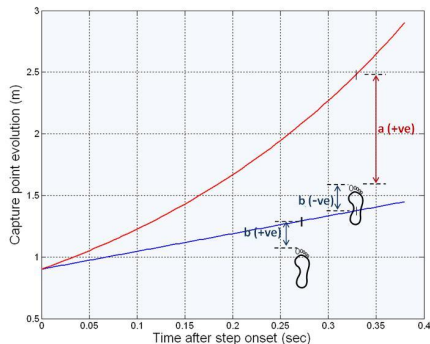
Model results

Actual foot placement w.r.t. estimations

Where do subjects actually step with respect to the estimations ?

Comparison with experimental results of foot placement

Case I: Large space provided

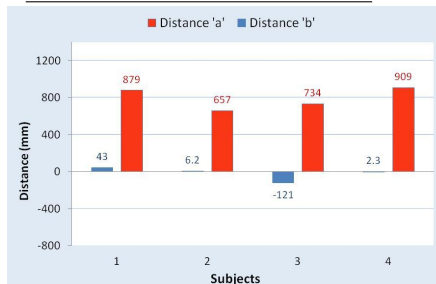


Model results

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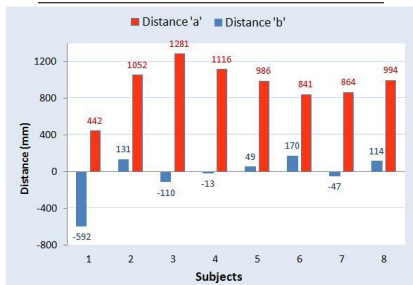
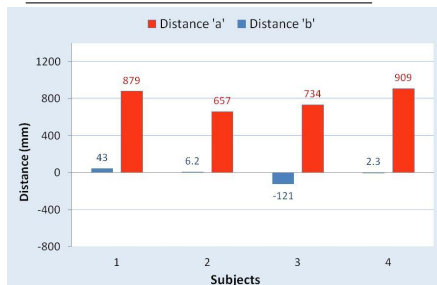
Comparison with experimental results of foot placement

Case I: Large space providedCase II: Limited space provided

Model results

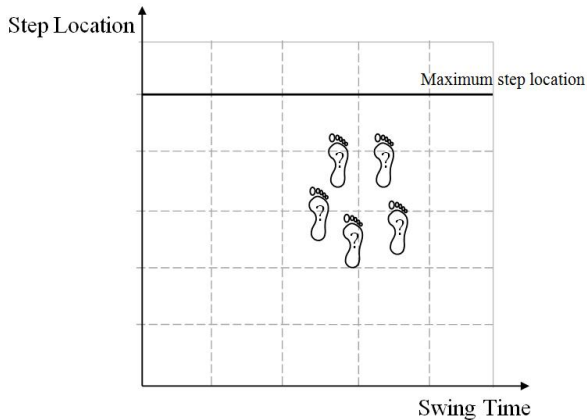
Actual foot placement w.r.t. estimations

Result 3 \Rightarrow Independent of no of steps taken, actual foot placement tend to be on or closer to the freefall line.

Case I: Large space providedCase II: Limited space provided

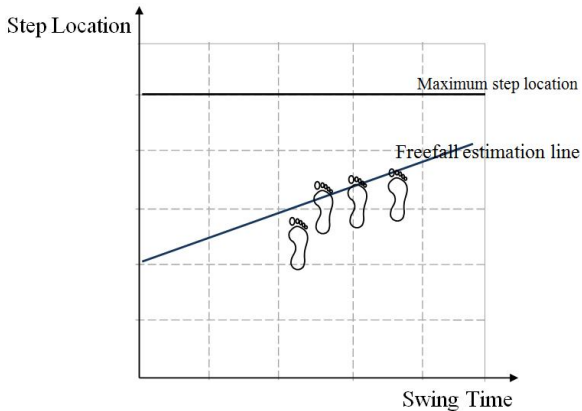
Consequence

Initial problem



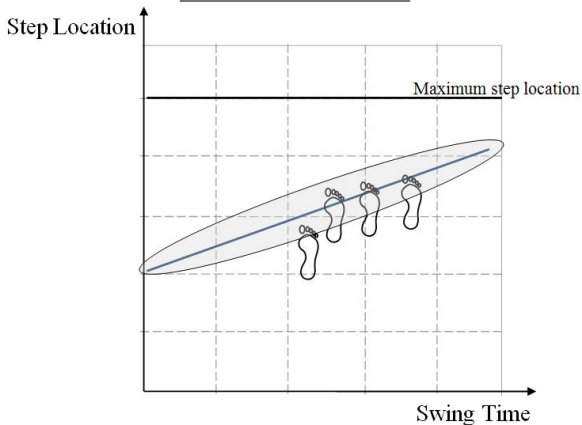
Consequence

Reduced problem



Consequence

Reduced problem



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Conclusion

- Linear inverted pendulum model is reasonably good for *single-step* recovery predictions
- The LIPM was not validated during the legswing phase
- The estimation of actual foot placement is better done by the freefall model in our case

Perspective

- Estimation of appropriate step time or step distance
 - Biomechanical constraints (e.g. Max step velocity)
 - Optimization criteria (e.g. Energy minimization)
 - Consideration of system dynamics and posture
- Choice of number of steps made by the subjects
- Exploitation of model predictive control schemes for foot placement⁶

⁶ Herdt et al., Online Walking Motion Generation with Automatic Foot Step Placement, Advanced Robotics,

Questions ?

